

The Beam Single Spin Asymmetry in Semi-inclusive Deep Inelastic Scattering

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Abstract

We study the beam single spin asymmetry in semi-inclusive hadron production in deep inelastic scattering in at order $1/Q$. There are two competing contributions: the leading order transverse momentum dependent parton distribution $h_1^\perp(x, k_\perp)$ convoluted with chiral-odd fragmentation function $\hat{e}(z)$, and the chiral-odd distribution function $e(x)$ convoluted with Collins fragmentation function $H_1^\perp(z, k'_\perp)$. We estimate this asymmetry and compare with the experimental measurements from CLAS and HERMES collaborations.

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The single spin asymmetry (SSA) is a novel phenomena in high energy spin physics, and has attracted much interest in recent years [1]. In particular, the measurements from the HERMES, SMC, and JLAB collaborations show a remarkably large SSA in the semi-inclusive deep inelastic scattering, such as pion production in $\gamma^*p \rightarrow \pi X$, when the proton is polarized transversely to the direction of the virtual photon [2, 3, 4]. On the theoretical side, there are many approaches to understanding SSA using Quantum Chromodynamics (QCD) phenomenology [1, 5]. Recent interest focuses on the transverse momentum dependent (TMD) parton distributions and their implications to the semi-inclusive processes in deep inelastic scattering [6, 7, 8, 9, 10, 11, 12, 13]. For example, the Sivers function is one of those TMD parton distributions representing the asymmetric distribution of quarks in a transversely polarized proton, which correlates the quark transverse momentum and the proton polarization vector \vec{S}_\perp [7]. It contributes to the target SSA in semi-inclusive deep inelastic scattering. The existence of the Sivers function has been confirmed recently [14, 15, 16, 17], where the final state interactions from the gauge link in the gauge invariant definition of TMD parton distributions play an important role.

In this paper, we will study the SSA related to the beam polarization. Unlike the target SSA, the beam SSA is subleading in $1/Q$, which will eventually vanish as $Q^2 \rightarrow \infty$. However, at some intermediate Q^2 , but still large enough to guarantee the factorization, this asymmetry might be important and measurable. Experimentally, HERMES collaboration found this asymmetry consistent with zero [2], but the CLAS collaboration at JLab found sizable asymmetry, in the order of 4% [18]. In the literature [10, 11, 19], this asymmetry has been associated with the twist-3 chiral-odd distribution function $e(x)$ [20] convoluted with the Collins fragmentation function $H_1^\perp(z, k'_\perp)$ [8]. However, this is not the complete picture at this order. There is an additional contribution: the leading order TMD parton distribution $h_1^\perp(x, k_\perp)$ [12] convoluted with a chiral-odd fragmentation function $\hat{e}(z)$ [9, 21]. We will demonstrate the existence of this contribution below.

The TMD parton distribution h_1^\perp represents the correlation between the quark's transverse momentum and polarization in an unpolarized proton state [12, 22]. It has the same features as the Sivers function: it is a leading-order distribution; it is nonvanishing due to the final state interactions; it depends on the quark orbital angular momentum of the nucleon [23]. Various model calculations have also shown that it has a similar size as the Sivers function [24, 25, 26]. On the other hand, since h_1^\perp is chiral-odd, it is very difficult to probe it in deep inelastic scattering, just like the transversity distribution. Our analysis shows that it contributes to the beam SSA, which can be used to extract the distribution itself. Another possible way to study h_1^\perp distribution is the asymmetry in the Drell-Yan process [22].

We first derive the beam SSA in deep inelastic scattering. The semi-inclusive hadron production cross section can be expressed as

$$\frac{d^5\sigma}{dx_B dy dz d^2P_{\perp h}} = \frac{2\pi\alpha^2}{4zx_B Q^2 s} L_{\mu\nu} W^{\mu\nu} , \quad (1)$$

where $L_{\mu\nu}$ and $W^{\mu\nu}$ are leptonic and hadronic tensors, respectively. We work in a frame where the virtual photon's momentum q and the proton's momentum P are in the z direction, and the incident and outgoing lepton's momenta \vec{l} and \vec{l}' form a scattering plane. We can define the azimuthal angle of any momentum as an angle relative to the scattering plane. The variable s is the lepton-hadron total energy square, $Q^2 = -q^2$ the virtuality of the photon, and the dimensionless variables x_B , y , and z are defined as $x_B = Q^2/2P \cdot q$, $y = P \cdot q/P \cdot l$,

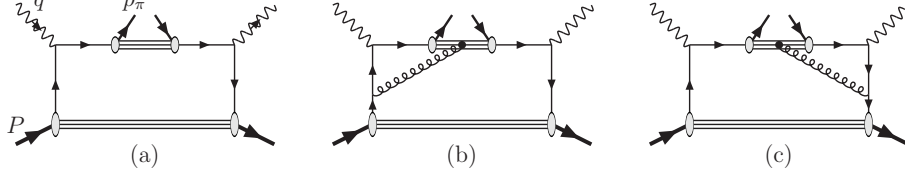


FIG. 1: The relevant diagrams contributing to the beam spin asymmetry associated with $h_1^\perp \otimes \hat{e}(z)$ for semi-inclusive pion production in deep inelastic scattering.

$z = P \cdot p_\pi / P \cdot q$. The variable $P_{\perp h}$ is the transverse component of the observed pion's momentum p_π . We further introduce two light-like vectors: p and n , which satisfy $p^2 = 0$, $n^2 = 0$, $p \cdot n = 1$, $p^- = 0$, and $n^+ = 0$. All momenta can be expressed in terms of p and n and the transverse momentum component. The leptonic tensor has the symmetric and anti-symmetric parts, $L_{\mu\nu} = -Q^2 g_{\mu\nu} + 2(l_\mu l'_\nu + l_\nu l'_\mu) + 2i\lambda_e \epsilon_{\mu\nu\rho\sigma} l^\rho l'^\sigma$, where λ_e is the polarization parameter of the lepton. The antisymmetric part will give the beam spin asymmetry, convoluted with the antisymmetric part of the hadronic tensor $W_a^{\mu\nu}$.

We follow the previous studies [9, 10, 11], and use QCD factorization to calculate the hadronic tensor $W^{\mu\nu}$, which can be separated into soft and hard parts. The hard part can be calculated in perturbative QCD; and the soft parts are nonperturbative and can be parameterized in Lorentz-invariant and gauge-invariant distribution and fragmentation functions. The relevant Feynman diagrams are shown in Fig. 1. The lower part of these diagrams represent the parton distribution of the target, and the upper part involves the fragmentation of a quark into a pion. The symmetric part of $W^{\mu\nu}$ in the leading order has a contribution from diagram (a). The antisymmetric part has two contributions. Since the contribution from the $e(x) \otimes H_1^\perp(z, k'_\perp)$ term has been calculated in Ref. [10], in the following we will focus on the contribution from the $h_1^\perp(x, k_\perp) \otimes \hat{e}(z)$ term. Because $\hat{e}(z)$ is a twist-3 fragmentation function, we need to include the diagrams (b) and (c) of Fig. 1 to get an electromagnetically gauge-invariant result.

The parton distributions can be defined from the following density matrix [6],

$$\mathcal{M}_p(x, k_\perp) = p^+ \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3} e^{-i(\xi^- k^+ - \vec{\xi}_\perp \cdot \vec{k}_\perp)} \langle PS | \bar{\psi}(\xi^-, \xi_\perp) \mathcal{L}^\dagger \mathcal{L} \psi(0) | PS \rangle, \quad (2)$$

where \mathcal{L} is the gauge link [15, 16]. The density matrix has the following expansion [12],

$$\mathcal{M}_p = \frac{1}{2} f_1(x, k_\perp) \not{p} + \frac{1}{2M} h_1^\perp(x, k_\perp) \sigma^{\mu\nu} k_\mu p_\nu + \dots, \quad (3)$$

where f_1 is the usual unpolarized unintegrated parton distribution, and both f_1 and h_1^\perp are leading order in twist counting.

Similarly, for the pion fragmentation functions, we can define the density matrix as [9, 10, 11],

$$\mathcal{M}_\pi(z, k'_\perp) = \frac{n^-}{2z} \int \frac{d\eta^+ d^2\eta_\perp}{(2\pi)^3} e^{-i(\eta^+ k'^- - \vec{\eta}_\perp \cdot \vec{k}'_\perp)} \langle 0 | \mathcal{L} \psi(\eta^+, \eta_\perp) | \pi X \rangle \langle \pi X | \bar{\psi}(0) \mathcal{L}^\dagger | 0 \rangle, \quad (4)$$

where $z = p_\pi \cdot p / k' \cdot p$, and $-\vec{z} \vec{k}'_\perp$ is the transverse momentum of pion relative to the quark's momentum. This fragmentation matrix density has the expansion [9],

$$\mathcal{M}_\pi = \frac{1}{2} \hat{f}_1(z, k'_\perp) \not{p} + \frac{1}{2} \frac{M_p}{p_\pi \cdot p} \hat{e}(z, k'_\perp) + \dots, \quad (5)$$

where \hat{f}_1 is the usual unpolarized unintegrated fragmentation function; and \hat{e} is the twist-3 chiral-odd fragmentation function. There are two twist-3 and chiral-odd fragmentation functions for the pion [21], but we only keep the one which contributes to beam SSA. As argued in [9, 21], instead of the pion mass, we put the nucleon mass as the coefficient in front of $\hat{e}(z, k'_\perp)$, because the pion mass vanishes in the chiral limit but the density matrix \mathcal{M}_π does not.

The contribution from Fig. 1(a) to the hadronic tensor $W^{\mu\nu}$ can be calculated as,

$$W^{\mu\nu(a)} = 2z \int d^2k_\perp d^2k'_\perp \delta^{(2)}(P_{\perp h}/z - k_\perp + k'_\perp) \text{tr} [\mathcal{M}_p \gamma^\mu \mathcal{M}_\pi \gamma^\nu] . \quad (6)$$

Substituting the expansions of the density matrices \mathcal{M}_p and \mathcal{M}_π , we have

$$W^{\mu\nu(a)} = 2z \int d^2k_\perp d^2k'_\perp \delta^{(2)}(P_{\perp h}/z - k_\perp + k'_\perp) \left\{ f_1(x, k_\perp) \hat{f}_1(z, k'_\perp) [p^\mu n^\nu + p^\nu n^\mu - g^{\mu\nu}] \right. \\ \left. + i h_1^\perp(x, k_\perp) \hat{e}(z, k'_\perp) \frac{1}{p_\pi \cdot p} [p^\mu k_\perp^\nu - p^\nu k_\perp^\mu] \right\} , \quad (7)$$

where the electric charge of the quark and the sum over all quark flavor are implicitly assumed. The first term in the bracket is the symmetric part of the tensor, and the second one antisymmetric. The symmetric part itself is electromagnetic gauge invariant, while the antisymmetric part is not, i.e., $q_\mu W^{\mu\nu(a)} \neq 0$. However, after including the contributions from diagrams (b) and (c) in Fig. 1, we can recover the gauge-invariance [9]. This leads to the following result for the antisymmetric part: $i2h_1^\perp(x, k_\perp) \hat{e}(z, k'_\perp)/z/Q^2 [T^\mu k_\perp^\nu - T^\nu k_\perp^\mu]$, where $T^\mu = 2xP^\mu + q^\mu$.

Including also the contributions from the convolution of $e(x)$ with the Collins function $H_1^\perp(z, k'_\perp)$ [10], we get the complete result for the antisymmetric part of the hadronic tensor at order $1/Q$,

$$W_a^{\mu\nu} = 2z \int d^2k_\perp d^2k'_\perp \delta^{(2)}(P_{\perp h}/z - k_\perp + k'_\perp) \left\{ i h_1^\perp(x, k_\perp) \frac{\hat{e}(z, k'_\perp)}{z} \frac{2}{Q^2} [T^\mu k_\perp^\nu - T^\nu k_\perp^\mu] \right. \\ \left. - i x e(x, k_\perp) H_1^\perp(z, k'_\perp) \frac{2}{Q^2} [T^\mu k'_\perp{}^\nu - T^\nu k'_\perp{}^\mu] \right\} , \quad (8)$$

and it contributes to the beam SSA. We modified the definition of the Collins function H_1^\perp in [10, 11] by a factor of M_p/m_π by the same argument we used in Eq. (5) for the fragmentation function $e(z)$. The definition of $e(x)$ follows [20]. Since T^μ is on order of Q , we see that the above antisymmetric part will contribute to the cross section in the order of $1/Q$. That means the beam SSA will be $1/Q$ suppressed, which is different from the Siverson effect contribution to the target SSA being the leading order effect.

Substituting the hadronic tensor into the differential cross section formula Eq. (1), we will get:

$$\frac{d^5\sigma}{dx_B dy dz d^2P_{\perp h}} = \frac{4\pi\alpha^2}{x_B y^2 s} \int d^2k_\perp d^2k'_\perp \delta^{(2)}\left(\frac{P_{\perp h}}{z} - k_\perp + k'_\perp\right) \left\{ (1 - y + \frac{y^2}{2}) f_1(x, k_\perp) \hat{f}_1(z, k'_\perp) \right. \\ \left. + \lambda_e \frac{2y\sqrt{1-y}}{Q} h_1^\perp(x, k_\perp) |\vec{k}_\perp| \frac{\hat{e}(z, k'_\perp)}{z} \sin \phi_k \right. \\ \left. - \lambda_e \frac{2y\sqrt{1-y}}{Q} x e(x, k_\perp) H_1^\perp(z, k'_\perp) |\vec{k}'_\perp| \sin \phi_{k'} \right\} , \quad (9)$$

where ϕ_k and $\phi_{k'}$ are the azimuthal angles of the momenta \vec{k}_\perp and \vec{k}'_\perp relative to the scattering plane, respectively. For example, we define $\sin \phi_k = \vec{l} \times \vec{l}' \cdot \vec{k}_\perp / |\vec{l} \times \vec{l}'| |\vec{k}_\perp|$. Since only one of the two transverse momenta k_\perp and k'_\perp is relevant for the $\sin \phi$ asymmetry, we can integrate out the other without assuming the transverse momentum dependence of the distribution and fragmentation functions. After that, the ϕ_k or $\phi_{k'}$ dependence leads to ϕ_h dependence, where ϕ_h is the azimuthal angle of the observed hadron relative to the scattering plane: $\sin \phi_h = \vec{l} \times \vec{l}' \cdot \vec{P}_{\perp h} / |\vec{l} \times \vec{l}'| |\vec{P}_{\perp h}|$. Finally,

$$\begin{aligned} \frac{d^5 \sigma}{dx_B dy dz d^2 P_{\perp h}} = & \frac{4\pi\alpha^2}{x_B y^2 s} \left\{ (1 - y + \frac{y^2}{2}) \int d^2 k_\perp \delta^{(2)}(P_{\perp h} - z k_\perp) f_1(x, k_\perp) \hat{f}_1(z) \right. \\ & + \lambda_e \frac{2y\sqrt{1-y}}{Q} \int d^2 k_\perp \delta^{(2)}(P_{\perp h} - z k_\perp) h_1^\perp(x, k_\perp) |\vec{k}_\perp| \frac{\hat{e}(z)}{z} \sin \phi_h \\ & \left. + \lambda_e \frac{2y\sqrt{1-y}}{Q} \int d^2 k'_\perp \delta^{(2)}(P_{\perp h} + z k'_\perp) x e(x) z^2 H_1^\perp(z, k'_\perp) |\vec{k}'_\perp| \sin \phi_h \right\}, \end{aligned} \quad (10)$$

where a sign has changed in the last term because \vec{k}'_\perp and $\vec{P}_{\perp h}$ have opposite directions. The integrated fragmentation functions are defined as $\hat{f}_1(z) = z^2 \int d^2 k'_\perp f_1(z, k'_\perp)$, the same for $\hat{e}(z)$, and the distribution function $e(x) = \int d^2 k_\perp e(x, k_\perp)$.

We can further simplify the differential cross section by integrating out the transverse momentum $P_{\perp h}$ but keeping the dependence on ϕ ,

$$\begin{aligned} \frac{d^5 \sigma}{dx_B dy dz d\phi} = & \frac{2\alpha^2}{x_B y^2 s} \left\{ (1 - y + y^2/2) f_1(x) \hat{f}_1(z) \right. \\ & + 2\lambda_e y \sqrt{1-y} \frac{M_p}{Q} h_1^{\perp(1/2)}(x) \frac{\hat{e}(z)}{z} \sin \phi \\ & \left. + 2\lambda_e y \sqrt{1-y} \frac{M_p}{Q} x e(x) H_1^{\perp(1/2)}(z) \sin \phi \right\}, \end{aligned} \quad (11)$$

where the integrated parton distribution $f_1(x) = \int d^2 k_\perp f_1(x, k_\perp)$, $h_1^{\perp(1/2)}(x) = \int d^2 k_\perp |k_\perp| / M_p h_1^\perp(x, k_\perp)$, and fragmentation $H_1^{\perp(1/2)}(z) = z^2 \int d^2 k'_\perp |k'_\perp| / M_p H_1^\perp(z, k'_\perp)$. If we write the differential cross section as $d\sigma \propto 1 + A_y \sin \phi$,

$$A_y = \frac{\lambda_e \int dy dz dx_B \frac{2y\sqrt{1-y}}{x_B y^2} \frac{M_p}{Q} \left(h_1^{\perp(1/2)}(x) \frac{\hat{e}(z)}{z} + x e(x) H_1^{\perp(1/2)}(z) \right)}{\int dy dz dx_B \frac{1-y+y^2/2}{x_B y^2} f_1(x) \hat{f}_1(z)}. \quad (12)$$

The x_B and z dependence of A_y can also be similarly calculated. We note that the two contributions have exactly the same dependence on y , which makes it difficult to distinguish them experimentally.

With known distribution and fragmentation functions, we can predict the beam SSA. However, up to now, except for the unpolarized quark distribution f_1 and fragmentation \hat{f}_1 , these functions can only be estimated in models. In addition, the model calculations are not consistent at the present stage. For example, controversial predictions exist for the Collins fragmentation function H_1^\perp [27, 28], and we have a wide range of predictions for the leading-order TMD parton distribution $h_1^\perp(x, k_\perp)$ from models [24, 25, 26]. So, a reliable model prediction is not possible at present. However, we can still gain some insight for these functions by comparison with the experimental data. For example, in [19], the beam SSA

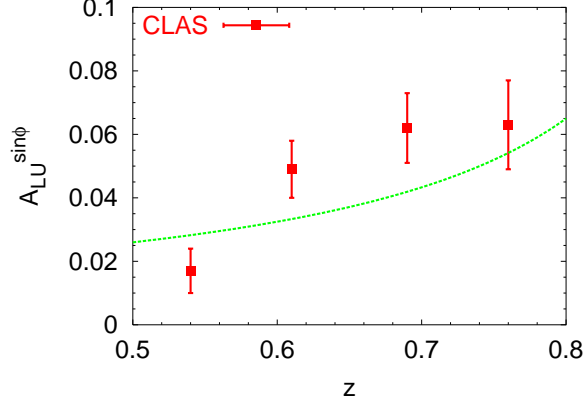


FIG. 2: The beam SSA prediction from $h_1^\perp(x) \otimes \hat{e}(z)$, compared with the experimental data from CLAS [18]. The z dependence solely comes from the ratio of the fragmentation functions $\hat{e}(z)/f_1(z)$.

has been interpreted as the result of the Collins effect, and the experimental data were used to extract the distribution function $e(x)$.

In this paper, we take an alternative extreme. We interpret the beam SSA as a result of the first term in Eq. (12). To compare with the experimental data, we assume that the factorization works at the energy range covered by the experiment. This contribution depends on the chiral-odd fragmentation function $\hat{e}(z)$, which has been calculated in a chiral quark model in [29]. To a good approximation, we have

$$\hat{e}(z) = \frac{z}{1-z} \frac{m_q}{M_n} \hat{f}_1(z) \approx \frac{1}{3} \frac{z}{1-z} \hat{f}_1(z), \quad (13)$$

where m_q is the constituent quark mass, and M_n the nucleon mass. The above relation is only true at the scale of Λ_χ , and at higher scale their relation might breakdown because the evolution of these two functions is different. However, as a rough estimate, we will adopt such approximations. The chiral quark model prediction for the usual unpolarized fragmentation function $\hat{f}_1(z)$ is consistent with the experimental data after considering the evolution effects [29]. We should also note that the chiral quark model is not suitable for the calculation of the fragmentation function at $z \rightarrow 1$ region, where the invariant mass of the fragmenting quark exceeds the cutoff of the model, Λ_χ .

The z dependence of the asymmetry A_y only comes from the ratio of the two fragmentation functions $\hat{e}(z)$ and $\hat{f}_1(z)$ in Eq. (12), and the simple relation Eq. (13) can be used to predict the z dependence of A_y . In Fig. 2, we show the normalized asymmetry prediction from this term compared with CLAS measurements. The most striking observation is that this simple relation Eq. (13) agrees with the experiment very well. The normalization of A_y also depends on the TMD parton distribution h_1^\perp . This distribution involves more complicated dynamics [24, 25, 26], and hence is less reliable compared to the fragmentation function $\hat{e}(z)$ in Eq. (13). Nevertheless, from what we have now for h_1^\perp , we can make an order-of-magnitude estimate and compare with experiment. For example, a bag model calculation shows that the ratio of $h_1^{\perp(1/2)}(x)/f_1(x)$ at the kinematic region of the CLAS measurement $0.15 < x < 0.4$ is about 0.04 for u quark [26]. After taking into account other kinematic factors in Eq. (12), the asymmetry A_y is predicted to be about 0.05, in rough agreement with the CLAS result of 0.038 [18], although the bag model prediction is very crude and the sign is inconsistent.

Extending the above estimate to the HERMES kinematics, the beam SSA is at least a factor of 5 less than what CLAS has found, consistent with the HERMES measurement [2]. This is just the consequence of the beam SSA being $1/Q$ effect. So, there is no contradiction between these two experiments. This also agrees with the observation of [19].

We note that another interpretation of the beam SSA has been made in [31], where the photon “Sivers” effect was considered. In Ref. [30], an $\mathcal{O}(\alpha_s^2)$ QCD effect to the beam SSA have also been investigated. We did not include these effects in our formalism.

In conclusion, we have calculated the beam single spin asymmetry in semi-inclusive hadron production in deep inelastic scattering. Up to $1/Q$, there are two contributions: the distribution $h_1^\perp(x, k_\perp)$ convoluted with fragmentation $\hat{e}(z)$, and $e(x)$ convoluted with $H_1^\perp(z, k_\perp)$. A simple chiral quark model prediction of $\hat{e}(z) \approx z/3/(1-z)\hat{f}_1(z)$ agrees well with the experimental data on the z dependence of the asymmetry. Further experimental data can provide more information on the extraction of the leading order TMD parton distribution h_1^\perp .

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